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NUMERICAL SIMULATION OF SELF-INDUCED RAINOUT USING A DYNAMIC CONVECTIVE CLOUD MODEL

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MASTER

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1. INTRODUCTION

Fallout of radioactivity from the atmospheric detonation of a nuclear weapon can produce a severe collateral damage hazard. This hazard can be mitigated by detonating the weapon as a free-air burst, i.e., far enough above the ground that the fireball does not contact the surface. For a free-air burst primary damage is inflicted by blast and thermal effects; the radioactive debris, which forms as submicron particles, is widely dispersed by atmospheric motion before falling to the ground.

If precipitation is falling in the vicinity of a nuclear burst, the radioactive debris particles can be entrained by the clouds and rapidly scavenged and deposited on the ground producing a severe collateral damage hazard. We have expended considerable effort at LLL trying to assess this hazard looking at microphysical, dynamic, and climatological aspects, and have concluded that a significant hazard would occur if the debris encounters precipitation before it is dispersed.[1] Because precipitation scavenging can occur only when it is raining, there is an upper limit on the probability of natural rainout of about 0.2.

The probability of a rainout collateral damage hazard could be considerably enhanced if the cloud produced by the nuclear detonation develops precipitation. We call the phenomenon of rapid deposition of nuclear weapons debris by a cloud caused directly by the explosion self-induced rainout. Several years ago we investigated this possibility using a dynamic convective cloud model to simulate the life cycle of a nuclear cloud with the result that precipitation occurred and a significant amount of radioactive debris was deposited.[2] On the basis of this simulation we surveyed the U.S. nuclear test data for evidence of self-induced rainout, but we did not find any. This was not particularly surprising for the Nevada tests because of the arid climate and the criterion to avoid precipitation. For the Pacific tests, where self-induced rainout would be more likely, the observers were situated 10 or more miles upwind of the detonation point and would not have seen precipitation falling from the base of the nuclear cloud if it occurred.

2. OBSERVATIONS AT HIROSHIMA AND NAGASAKI

About the time we completed our survey of the test data, we were told about the "black rain" that accompanied the nuclear events at Hiroshima and Nagasaki, Japan. "There has always been concern by survivors who were exposed to the so-called 'black rain' . . . The updraft caused by the nuclear explosions drew much debris and dust into the atmosphere. The ensuing turbulence generated rain showers in both cities beginning about half an hour after the blast. The first rain that fell was described as black, probably because it washed the dust and smoke from the burning cities out of the air. A number of survivors who had not been near enough to the explosion to receive significant initial exposures were caught in the black rain; they reported radiation-inducible symptoms."[3] Concern about exposure to "black rain" was great enough that one of the items in the survivor reports, which were compiled for thousands of survivors, dealt specifically with this phenomenon.

Evidence of radioactivity on the ground in the suburbs of Hiroshima was obtained by the Second Japanese Investigation on 13-14 August 1945. "Samples found in the area 3.5 km northwest of the hypocenter demonstrated considerably intense radiation. This is believed to be due to the fall of bomb fragments as a result of meteorological conditions at the time of the explosion."[4] "At that time [3-4 September 1945], in addition to the maximum residual gamma rays about twice as intensive as the background in the vicinity of the hypocenter, we detected on the Sanyo National Highway between Koi and Kusatsu [~3 km west of the hypocenter], gamma rays of about the same intensity as in the vicinity of the hypocenter, . . . The cause of this radiation is considered to be different from that in the vicinity at the hypocenter and for the following reasons it is felt that uranium nuclear fission products of the A-bomb explosion had fallen. That is, at the time of the explosion, an east wind was blowing in this area and there was much rain in this area about 30 minutes after the explosion. This rain is reported to have been black and dirty. Furthermore, evidence that this was due to fallout is that especially intensive radiation was found in mud which had collected in an eaves trough of a house . . . Chemical analysis was conducted on a part of it (mud collected from eaves trough of a small house below the Ueno Garden where the intensity of radiation was greatest) . . . and uranium nuclear fission products were confirmed to be present."[5]

"Radioactivity in the vicinity of Nishiyama Reservoir in Nagasaki City [Nishiyama Reservoir is 3 km east of the hypocenter] was measured and found to be far greater than that of the hypocenter area . . . In the latter area [Nishiyama], radioactivity was found over a wide area covering more than 10 km^2, . . . at some places being as high as over 25 times as strong as that in the hypocenter area [on 1 October 1945]. Since Nishiyama area was downwind from the hypocenter — a wind of 3 meters per second was blowing then — the rain which fell about 20 minutes later must have washed down radioactive substances with the dust blown up over Nagasaki City . . . The vicinity of Nishiyama being a hilly area, heavy rains which fell several times following the A-bomb detonation before the measurements were started washed away almost all the radioactive substances on the road. Therefore, grassy areas along the roadside were chosen for measurement and strong radioactivity was usually found in such places."[6]

Some of the details of the "black rain" are given in The Report of the Atomic Bomb Damage in Hiroshima.[7] "20 to 30 minutes after the blast, the black clouds nimbostratus moved towards the north-northwest and it distinctly caused to produce the phenomena of rain shower. The showers occurred between the hours of 0900-1600 . . . Fire became widespread from about 0900 hours, was at its height between 1000 and 1400 hours and slackened in the evening . . . This [motion of clouds and smoke to the NW] shows that a southeastern wind was blowing in the upper region at an altitude ranging from 500 to several thousand meters. Its estimated velocity is 1 to 3 m sec^{-1}. We regret that we are unable to make a study on actual observations as we do not have in hand the observation reports on the upper air currents of that day. [As far as I can determine, they have never been found.] The rainfall on this occasion came of two-fold influences, one being the direct influence of upward air current caused by the explosion itself and the other being the indirect influence of the upward air current caused by the fire after bombing.

"The hour of initial rainfall ranges from 15 minutes to 4 hours after observation of the flash of the explosion, but in most places it began raining from 20 minutes to an hour after . . . The rain stopped between 0900 and 0930 hours at the earliest points and between 1500 and 1600 hours at the latest . . . It may be concluded that the dust and soot in the air were for the most part washed down to be left on the ground during the first 1 to 2 hours of rainfall . . . I regret that we cannot give a definite figure of the amount of rainfall in the present case as there was not a single meteorological observation unit established in this area of rainfall. But judging from the fact that there appeared almost the same rise in water level in the same short hours in the mountain streams in Koi as well as in the Yasu River . . . as on the occasion of the typhoon experienced on 17 and 18 September [1945]; it is estimated that the rainfall in the area of downpour amounted to 50-100 mm within 1 to 3 hours of rain."

"In Nagasaki . . ., there was a shower phenomena far smaller in scale as compared with that of Hiroshima. This is probably due to reasons of the absence of frontier air current zones as was seen in Hiroshima and the far smaller scale of the fire at the former city, which became additional influential factors to the rain-forming conditions."[7]

Isodose contours for Nagasaki as measured with Geiger counters by the U.S. First Technical Group of the Manhatten Engineering District are shown in Fig. 1. These data were taken ~60 days after the events and after 2 typhoons had swept through Southern Japan, but they appear generally consistent with the crude Japanese measurements obtained pre-typhoon. Arakawa[8] estimates the external integrated gamma dose at about 100 rads in Nishiyama compared to several rads in the western suburbs at Hiroshima.

My conclusions are that deposition of radioactive debris by precipitation occurred at both Hiroshima and Nagasaki, and that the precipitation was initiated by the explosion itself and by the ensuing fires. Additional meteorological data and films of these detonations suggest that precipitation would not have occurred naturally. The deposited radioactivity was a small fraction of the debris produced by the nuclear detonation, but the contours presented are subject to considerable uncertainty due to questions regarding the mix of radioactive decay products and changing decay rates and because of weathering during the time between deposition and measurement.

3. SIMULATION OF NAGASAKI EVENT

During our rainout reseach we developed a two-dimensional axisymmetric convective cloud model of precipitation scavenging. The cloud dynamics and microphysics were taken from the Rand Cumulus Dynamics Model.[9] We developed a representation for scavenging of sub-micron aerosols for this model that is compatible with the Kessler microphysics parameterization. We have used this model to simulate the scavenging and deposition of radioactive weapons debris by natural convective clouds.

Since we had this model available, we used it in an attempt to simulate self-induced rainout.[2] This was done with the realization that this application of the model violates one of the basic dynamic assumptions, that the density perturbation of the atmosphere is small. Nevertheless, the simulation produces an acceptable simulation of nuclear cloud rise and is considered reasonably realistic.

The major difference between a simulation of self-induced rainout and natural convection is the initial perturbation. For the simulation of the Nagasaki event, we used a weapons yield of 22 kT, and extracted data on initial temperature (3000°C) and fireball radius (230 m) from Ref. 10. We further assumed this thermal energy had a $\cos^2(R)$ distribution from a maximum at the center to ambient at a radius of twice the fireball size. The radioactivity was assumed to have a similar distribution.

The simulation was started from rest with this assumed perturbation and run with an initial grid spacing of 100 m from 0-30 sec. At this point the grid spacing was changed to 300 m and the model restarted using the motion field, temperature and debris distributions at 30 sec. No condensation had occurred at this time. With a 300 m grid spacing the domain of the model was height 13.5 km, radius 9 km.

The development of the cloud clearly depends on the vertical structure of the atmosphere. We have not been able to find any upper air data taken in Japan at this time, apparently it has been destroyed. We did find data from a series of weather reconnaissance missions flow by USAF over Japan from Guam. As planes approached the Japanese Islands from the east they ascended from about 2000 ft altitude to 30,000 ft and took measurements of temperature at 1000 ft intervals. Only one of these flights recorded humidity data, a flight on the morning of 9 August (the day of

Nagasaki bombing); we used the sounding from this flight in the simulation for Nagasaki. Since the data ends at 30,000 ft, we placed the tropopause at that altitude although it was probably quite a bit higher since there was a high pressure region centered just east of Japan at this time. In the simulation the nuclear cloud rises to this tropopause in about 4 minutes, after which the buoyancy term becomes negative and the upward velocity decreases. The cloud is also approaching the top boundary of the model. In the streamfunction-vorticity formulation, the upward velocity tends to be deviated to radially outward, but this is a minor effect in this particular simulation.

Sub-grid motions are represented in our model by a Fickian diffusion term. We have used a diffusion coefficient of 400 m^2 sec^{-1}, a very high value even for convective clouds but perhaps not unrealistic for nuclear weapons clouds particularly at early times. The model results are fairly dependent upon the value of this parameter.

An axi-symmetric model cannot represent the horizontal motion of the external atmosphere and particularly wind shear. Even a relatively small horizontal wind shear can dramatically affect the development of the cloud. Films of the Nagasaki event suggest that the wind shear was small, but not insignificant, and the distribution of deposited radioactivity suggest downwind transport of the debris at about 3 m sec^{-1}. We assumed in plotting our simulated deposition patterns that the cloud moved as a whole with a velocity of 5 m sec^{-1}.

The scavenging parameterization envisions a two-step removal process. Sub-micron debris particles are assumed to become attached to or incorporated in cloud droplets at a rate of 10^{-4} sec^{-1}. These debris-laden droplets can be inertially captured by raindrops, which transport the debris to the ground. Total evaporation of droplets and raindrops before they reach the ground leads to resuspension of radioactivity in the atmosphere. In the simulation there was no scavenging of debris by nucleation or direct attachment to raindrops.

Of the radioactivity entrained into the cloud in the simulation of the Nagasaki event only 14 percent is captured by droplets and only 3 percent is deposited on the ground by raindrops. The remainder is left suspended in the atmosphere after precipitation stops and the cloud dissipates.

In the simulation initial condensention occurs at $\sim$2 minutes after burst, and rain starts falling at 5 minutes. The cloud base is 1.2 km and maximum cloud top is 13.2 km. Rain continues for 30 minutes with maximum accumulation, assuming no cloud motion, of 8.5 mm. Maximum rain rate at cloud center of 31 mm/hr occurs at 18 minutes.

The surface distribution pattern of deposited radioactivity, assuming a 5 m sec^{-1} wind, is given in Fig. 2. This pattern can be compared with the measured patterns given in Fig. 1. We feel these patterns compare very favorably given the uncertainties in both the simulation and the observations. The greater downwind displacement in the simulation is due primarily to an overestimate of the mean wind.

4. CONCLUSIONS

The hypothesis that self-induced rainout can occur is supported by observations in Hiroshima and Nagasaki, where deposition of weapons debris with precipitation occurred several km downwind of the burst point. This precipitation was initiated either directly by the nuclear weapons or by the ensuing fires.

Simulation of the Nagasaki event with a convection cloud precipitation scavenging model, although fraught with many questionable assumptions, agrees surprisingly well with the observations and supports the hypothesis that self-induced rainout can occur.

5. ACKNOWLEDGMENT

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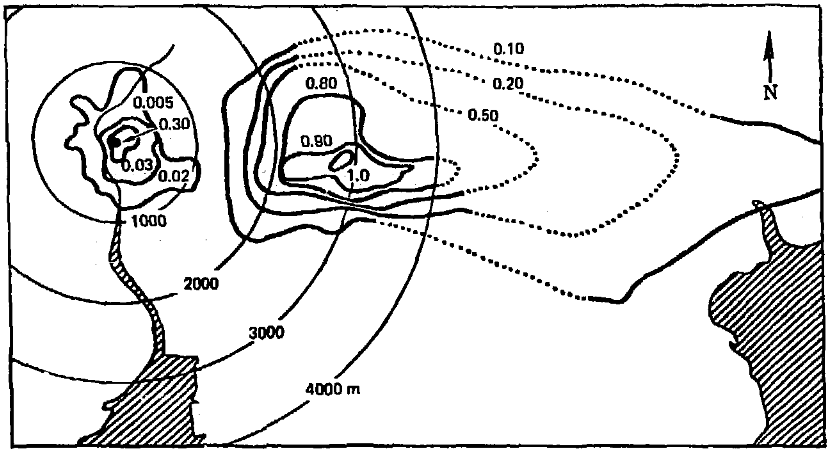

FIGURE 1. Isodose contours evaluated in milliroentgens per hour for October 3-7, 1945, at Nagasaki. Figure reproduced from Ref. 8.

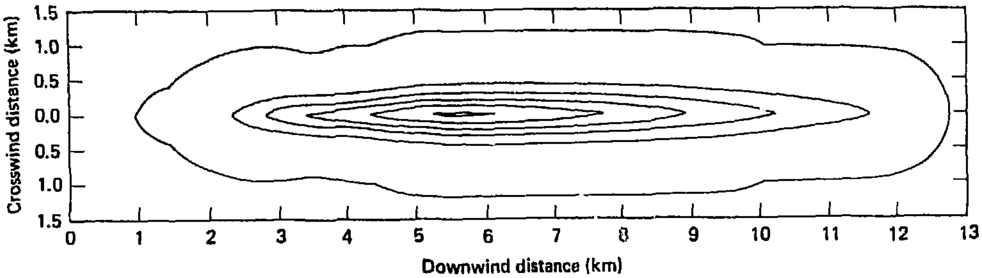

FIGURE 2. Isodose contours calculated by the scavenging model for Nagasaki assuming 5 m sec^{-1} wind. Contour levels are 500, 400, 300, 200, 100, 0 rad hr^{-1} at H+1 hour. The maximum dose rate is ~25 times the comparable measured dose rate.

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